

Influence of Land Cover and Watershed Scale on Climate-Streamflow Relationships in the Upper Midwest

Brooke Payne, Molly Wells, Katherine Clancy

College of Natural Resources, University of Wisconsin at Stevens Point, Stevens Point, WI, USA

Email: kclancy@uwsp.edu

How to cite this paper: Payne, B., Wells, M. and Clancy, K. (2026) Influence of Land Cover and Watershed Scale on Climate-Streamflow Relationships in the Upper Midwest. *Open Journal of Modern Hydrology*, **16**, 422-447.

<https://doi.org/10.4236/ojmh.2026.164023>

Received: June 28, 2026

Accepted: October 20, 2026

Published: October 23, 2026

Copyright © 2026 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

Understanding how land cover influences hydrologic response is critical for interpreting regional variability in streamflow. This study examines how climate-streamflow relationships vary across watersheds differing in land-cover composition, land-cover change, and watershed scale across 73 USGS-gauged watersheds in the Upper Midwestern United States. To reduce the confounding influence of climatic variability, climate conditions were characterized using the Standardized Precipitation-Evapotranspiration Index (SPEI). Hydrologic response was evaluated using baseflow and total streamflow derived from daily discharge records. Results reveal a pronounced north-to-south gradient in hydrologic behavior associated with land cover and long-term landscape change. Northern watersheds, dominated by forest cover and exhibiting minimal land cover change, show higher and more stable baseflow and relatively consistent, though dampened, relationships with SPEI. Central watersheds display intermediate conditions characterized by mixed land cover, moderate change, and localized areas of strong climate-baseflow coupling. Southern watersheds, characterized by extensive agriculture, increasing development, and greater land cover change, exhibit lower baseflow contributions, greater hydrologic variability, and more heterogeneous correlations with SPEI. Watershed scale also influences these relationships. Larger watersheds exhibit stronger and more stable correlations with climatic variability, whereas smaller watersheds show weaker and more variable responses, particularly in the southern region. Overall, hydrologic responses differ systematically with land cover and watershed size despite broadly similar climatic forcing. These findings demonstrate that climatic indices alone are insufficient to reliably predict hydrologic behavior in human-modified watersheds.

Keywords

Streamflow, Land Cover Changes, SPEI

1. Introduction

Understanding how land cover patterns and long-term land cover change influence streamflow, particularly baseflow, is essential for interpreting watershed hydrologic responses. Although precipitation and evapotranspiration determine water availability, streamflow responses are strongly shaped by land cover, landscape structure, and watershed scale. As a result, similar climatic conditions can produce markedly different hydrologic behaviors. This is especially true in the Great Lakes states of the upper Midwest, where strong land cover gradients and widespread human modification contribute to significant hydrologic variability and nonstationarity [1] [2].

Baseflow, the groundwater contribution to streamflow, links climate inputs to watershed storage by reflecting recharge, storage, and subsurface connectivity [3] [4]. Because it depends on groundwater processes, baseflow is particularly sensitive to land cover influences on infiltration, evapotranspiration, and subsurface flow. In contrast, total streamflow includes both baseflow and rapid runoff. Evaluating these components separately helps identify how landscape characteristics affect hydrologic response. Standardized baseflow metrics have also been shown to detect long-term hydrologic changes and relate watershed attributes to observed flow behavior across scales [5] [6].

The Great Lakes region exhibits a pronounced south-to-north land cover gradient. Southern watersheds are dominated by agriculture and increasing urbanization, while northern watersheds remain largely forested and contain more wetlands. These differences, driven by both climate and historical land use change, are associated with distinct patterns of baseflow, drought response, and long-term streamflow trends [7]-[9].

Land cover change has substantially altered streamflow dynamics throughout the Midwest. Conversion of perennial vegetation to row-crop agriculture has been linked to reduced evapotranspiration, increased groundwater recharge, and higher baseflow and streamflow. Tile drainage further modifies hydrologic pathways by accelerating subsurface flow and altering streamflow timing. Consequently, streamflow trends often reflect the combined influence of climate and land management rather than climate alone [10]-[13].

Urbanization adds further complexity. Impervious surfaces generally reduce infiltration and increase runoff, but wastewater return flows and infrastructure leakage can offset these effects and produce nonlinear responses. In some highly modified southern watersheds, increasing baseflow trends have been observed despite expectations of reduced recharge, highlighting the combined effects of climate variability and human activity [14]-[17].

Distinguishing climate-driven variability from land cover-mediated hydrologic response remains a major challenge. The Standardized Precipitation Evapotranspiration Index (SPEI) represents climatic water balance by combining precipitation and atmospheric demand, but it does not fully capture hydrologic buffering from soil moisture and groundwater storage. Because watershed responses may lag climatic signals, comparisons among SPEI, baseflow, and streamflow provide insight into where climate controls dominate and where landscape effects are important [3] [18].

Watershed scale also influences hydrologic behavior. Larger basins tend to produce smoother responses to climatic variability, whereas smaller watersheds are more sensitive to local land cover conditions. Geology, storage capacity, and subsurface connectivity further influence the partitioning of precipitation between runoff and groundwater contributions.

This study examines how climate-streamflow relationships vary among watersheds characterized by different land-cover patterns, land-cover histories, and watershed sizes across 73 U.S. Geological Survey gauged watersheds in the Great Lakes states of the upper Midwest. Relationships among SPEI, baseflow, and streamflow are analyzed to separate climate-driven responses from those associated with landscape characteristics while evaluating the influence of watershed scale.

Results show systematic variation along the regional land cover gradient. Southern watersheds, historically agricultural but increasingly urbanized, exhibit the greatest decoupling between SPEI and baseflow, suggesting that development weakens links between climatic water balance and groundwater contributions to streamflow. In contrast, northern forested and central mixed-land-cover watersheds maintain stronger relationships, reflecting lower disturbance and greater subsurface connectivity.

By integrating climate, land cover, and watershed scale, this study improves understanding of how landscape transformation influences hydrologic response across the Great Lakes region and contributes to growing evidence that baseflow variability reflects interactions among climate variability, land use, watershed structure, and groundwater dynamics.

2. Methods

2.1. Site Location Description

The study includes a set of 73 United States Geological Survey (USGS) gauged watersheds distributed across the upper Midwestern United States, spanning a latitudinal gradient from approximately 41°N to 49°N (Figure 1). Sites were selected to ensure there were no regulated flows and for completeness of the station's daily discharge record (Table 1). Of the 73 stations, 23 exhibited some missing daily discharge observations within their period of record. However, most missing observations occurred in isolated historical periods and did not affect the years used to compute annual streamflow, baseflow, BFI, and SPEI metrics. The remaining

stations had complete daily records over the analysis period.

Following regional frameworks used in previous studies of hydrologic variability across the Great Lakes and Upper Midwest [19], [20], watersheds are grouped into three geographic regions: southern ($41^{\circ}\text{N} - 43.5^{\circ}\text{N}$), central ($43.5^{\circ}\text{N} - 45^{\circ}\text{N}$), and northern ($>45^{\circ}\text{N}$). These divisions reflect well-established hydroclimatic and physiographic gradients in climate, land cover, and groundwater influence that structure streamflow and baseflow response. Prior work has demonstrated strong spatial heterogeneity across these regions, with northern watersheds exhibiting greater variability and stronger groundwater control on hydrologic processes [19] [20].

Watershed drainage areas span over two orders of magnitude, ranging from approximately 22 km^2 to 9495 km^2 . To enable comparison across scales, watersheds are classified into three size categories: small ($<500 \text{ km}^2$), medium ($500 - 1600 \text{ km}^2$), and large ($>1600 \text{ km}^2$). These thresholds are consistent with standard hydrologic scaling frameworks, where basin area serves as a primary control on runoff generation, storage, and flow-path integration, and align with commonly applied distinctions between headwater systems, intermediate basins, and regional river networks [21].

Small watersheds generally represent headwater systems with shorter flow paths and higher sensitivity to localized climatic and land use influences. Medium watersheds integrate processes across mixed land cover and intermediate groundwater contributions, while large watersheds reflect regional flow systems with longer residence times and greater hydrologic integration. Observations from Midwest baseflow studies indicate that groundwater contributions and variability tend to increase with watershed scale and stream network extent, reflecting greater subsurface connectivity in larger basins [2].

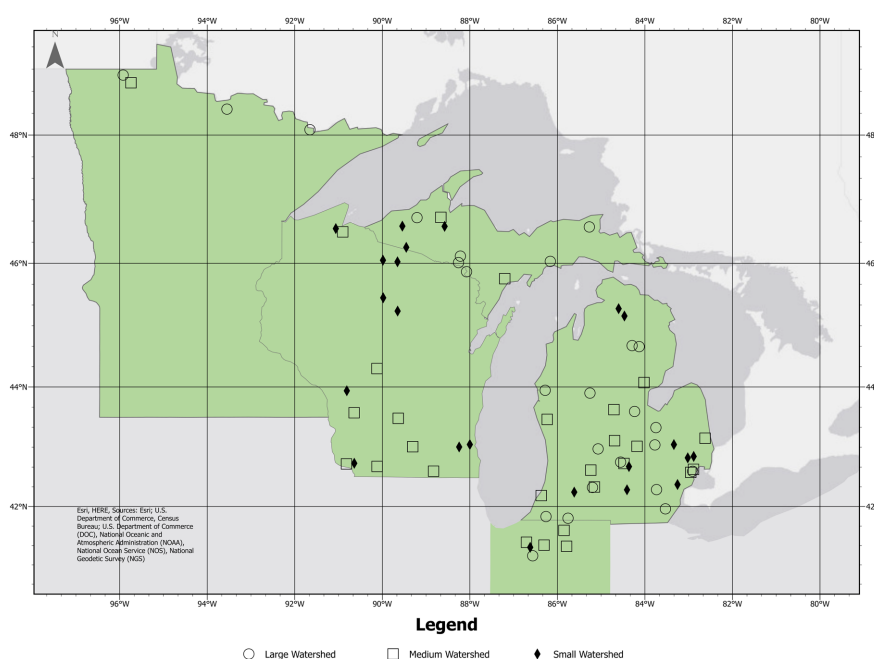


Figure 1. Map of the Site locations in the upper Midwest.

Watershed size distribution varies systematically across the study domain. Northern watersheds include a higher proportion of large drainage basins, central watersheds exhibit a mix of medium and large systems, and southern watersheds are dominated by small- to medium-sized basins. This pattern is consistent with regional hydrogeologic structure and glacial landscape controls, as well as documented north-south gradients in groundwater contributions and hydrologic variability across the Upper Midwest [19] [20].

Table 1. Summary table of USGS Gauging Stations used in this study.

Site No.	Station Name	Location	Record Start	Record End	Missing Days	Latest Missing Start	Latest Missing End
03330500	TIPPECANOE RIVER AT OSWEGO, IN	southern	10/1/1949	9/12/2026	5		
04027500	White River Near Ashland, WI	north	5/13/1948	9/12/2026	3		
04036000	WEST BRANCH ONTONAGON RIVER NEAR BERGLAND, MI	north	7/19/1942	9/12/2026	0		
04037500	CISCO BRANCH ONTONAGON R AT CISCO LAKE OUTLET, MI	north	10/1/1944	9/12/2026	0		
04040000	ONTONAGON RIVER NEAR ROCKLAND, MI	north	6/1/1942	9/12/2026	0		
04041500	STURGEON RIVER NEAR ALSTON, MI	north	2/1/1932	9/12/2026	493	7/29/2026	9/2/2026
04045500	TAHQUAMENON RIVER NEAR PARADISE, MI	north	8/7/1953	9/12/2026	0		
04056500	MANISTIQUE RIVER NEAR MANISTIQUE, MI	north	3/26/1938	9/11/2026	8		
04059500	FORD RIVER NEAR HYDE, MI	north	10/1/1954	9/12/2026	0		
04062000	PAINT RIVER NEAR ALPHA, MI	north	6/7/1952	9/12/2026	0		
04062500	MICHIGAMME RIVER NEAR CRYSTAL FALLS, MI	north	8/20/1944	9/12/2026	0		
04063522	MENOMINEE RIVER AT US HWY-2 NEAR IRON MOUNTAIN, MI	north	1/2/1914	8/11/2026	16	7/22/2026	8/6/2026
04087120	Menomonee River at Wauwatosa, WI	southern	10/1/1961	9/12/2026	0		
04099000	ST. JOSEPH RIVER AT MOTTVILLE, MI	southern	12/1/1923	9/12/2026	9		
04100500	ELKHART RIVER AT GOSHEN, IN	southern	10/1/1931	9/12/2026	0		
04101500	ST. JOSEPH RIVER AT NILES, MI	southern	10/1/1930	9/12/2026	0		
04102500	PAW PAW RIVER AT RIVERSIDE, MI	southern	10/1/1951	9/12/2026	1		
04105000	BATTLE CREEK AT BATTLE CREEK, MI	southern	10/30/1930	9/12/2026	598	8/6/1933	12/31/1933
04105500	KALAMAZOO RIVER NEAR BATTLE CREEK, MI	southern	7/27/1937	9/12/2026	0		
04106400	WEST FORK PORTAGE CREEK AT KALAMAZOO, MI	southern	9/10/1959	9/12/2026	0		
04109000	GRAND RIVER AT JACKSON, MI	southern	4/1/1935	9/12/2026	0		

Continued

04112000	SLOAN CREEK NEAR WILLIAMSTON, MI	southern	6/1/1954	9/12/2026	0		
04112500	RED CEDAR RIVER AT EAST LANSING, MI	southern	8/31/1902	9/12/2026	9921	1/1/1904	2/28/1931
04113000	GRAND RIVER AT LANSING, MI	southern	3/1/1901	9/12/2026	10,228	9/30/1906	9/30/1934
04115000	MAPLE RIVER AT MAPLE RAPIDS, MI	southern	8/1/1944	9/12/2026	0		
04116000	GRAND RIVER AT IONIA, MI	southern	3/19/1931	9/12/2026	7325	7/1/1931	7/20/1951
04117500	THORNAPPLE RIVER NEAR HASTINGS, MI	southern	10/1/1944	9/12/2026	0		
04121500	MUSKEGON RIVER AT EVART, MI	central	7/1/1931	9/12/2026	930	7/1/1931	1/15/1934
04122200	WHITE RIVER NEAR WHITEHALL, MI	central	8/1/1957	9/12/2026	0		
04122500	PERE MARQUETTE RIVER AT SCOTTVILLE, MI	central	8/1/1939	9/12/2026	2		
04127997	STURGEON RIVER AT WOLVERINE, MI	north	4/1/1942	9/12/2026	0		
04128990	PIGEON RIVER NEAR VANDERBILT, MI	central	10/1/1950	9/12/2026	0		
04136500	AU SABLE RIVER AT MIO, MI	central	7/9/1952	9/12/2026	0		
04142000	RIFLE RIVER NEAR STERLING, MI	central	1/13/1937	9/12/2026	0		
04144500	SHIAWASSEE RIVER AT OWOSSO, MI	southern	3/1/1931	9/12/2026	0		
04146000	FARMERS CREEK NEAR LAPEER, MI	southern	4/1/1933	9/12/2026	0		
04148500	FLINT RIVER NEAR FLINT, MI	southern	8/18/1932	9/12/2026	0		
04151500	CASS RIVER AT FRANKENMUTH, MI	southern	3/1/1908	9/12/2026	10,703	9/30/1936	6/19/1939
04154000	CHIPPEWA RIVER NEAR MOUNT PLEASANT, MI	central	10/1/1930	9/12/2026	367	9/30/1931	9/30/1932
04156000	TITTABAWASSEE RIVER AT MIDLAND, MI	central	4/1/1936	9/12/2026	42	1/19/2026	2/20/2026
04159492	BLACK RIVER NEAR JEDDO, MI	southern	3/1/1944	9/12/2026	2		
04164000	CLINTON RIVER NEAR FRASER, MI	southern	6/1/1947	9/12/2026	0		
04164100	EAST POND CREEK AT ROMEO, MI	southern	9/1/1958	9/12/2026	2		
04164300	EAST BRANCH COON CREEK AT ARMADA, MI	southern	10/1/1958	9/12/2026	0		
04164500	NORTH BRANCH CLINTON RIVER NEAR MT. CLEMENS, MI	southern	6/1/1947	9/12/2026	0		
04165500	CLINTON RIVER AT MORAVIAN DRIVE AT MT. CLEMENS, MI	southern	5/1/1934	9/12/2026	0		
04166500	RIVER ROUGE AT DETROIT, MI	southern	10/1/1930	9/12/2026	0		
04174500	HURON RIVER AT ANN ARBOR, MI	southern	1/1/1914	9/12/2026	305	10/1/1947	7/31/1948
04176500	RIVER RAISIN NEAR MONROE, MI	southern	9/1/1937	9/12/2026	0		
05104500	ROSEAU RIVER BELOW SOUTH FORK NEAR MALUNG, MN	north	10/1/1946	9/12/2026	207	8/2/2026	8/21/2026
05107500	ROSEAU RIVER AT ROSS, MN	north	8/1/1928	9/12/2026	1301	8/24/2026	8/27/2026
05127500	BASSWOOD RIVER NEAR WINTON, MN	north	1/1/1931	9/12/2026	151	1/1/1938	5/31/1938

Continued

05131500	LITTLE FORK RIVER AT LITTLEFORK, MN	north	7/1/1909	9/12/2026	4302	7/15/2026	7/16/2026
05357215	Allequash Creet at County Highway M Near Boulder Junction, WI	north	5/29/1991	7/2/2024	0		
05357335	Bear River Near Manitowish Waters, WI	north	5/1/1991	9/12/2026	1		
05382325	LaCrosse River at Sparta, WI	central	7/1/1992	9/12/2026	1096	9/14/2026	9/14/2026
05393500	Spirit River at Spirit Falls, WI	north	4/10/1942	9/12/2026	0		
05394500	Prairie River Near Merrill, WI	north	1/1/1914	9/12/2026	2878	9/30/1931	8/16/1939
05402000	Yellow River at Babcock, WI	central	3/25/1944	9/12/2026	336	4/9/2018	4/9/2018
05405000	Baraboo River Near Baraboo, WI	central	12/18/1913	9/12/2026	7482	8/24/2026	8/24/2026
05408000	Kickapoo River at La Farge, WI	central	10/1/1938	9/12/2026	1		
05413500	Grant River at Burton, WI	southern	10/1/1934	9/12/2026	0		
05414000	Platte River near Rockville, WI	southern	10/1/1934	9/12/2026	0		
05429500	Yahara River at McFarland, WI	southern	9/10/1930	9/12/2026	0		
05431486	Little Turtle Creek at Carvers Rock Road Near Clinton, WI	southern	9/25/1939	9/12/2026	0		
05432500	Pecatonica River at Darlington, WI	southern	9/27/1939	9/12/2026	0		
05515500	KANKAKEE RIVER AT DAVIS, IN	southern	10/1/1925	9/12/2026	915	7/15/2026	7/16/2026
05516500	YELLOW RIVER AT PLYMOUTH, IN	southern	10/1/1948	9/12/2026	2		
05517000	YELLOW RIVER AT KNOX, IN	southern	10/1/1943	9/12/2026	2		
05517500	KANKAKEE RIVER AT DUNNS BRIDGE, IN	southern	10/1/1948	9/12/2026	1		
05543830	Fox River at Waukesha, WI	southern	1/1/1963	9/12/2026	0		
040263491	North Fish Creek Near Moquah, WI	north	10/1/1989	9/29/2015	3379	9/30/2010	3/31/2014
04040500	STURGEON RIVER NEAR SIDNAW, MI	north	10/1/1912	9/12/2026	10,438	9/30/1915	3/31/1943

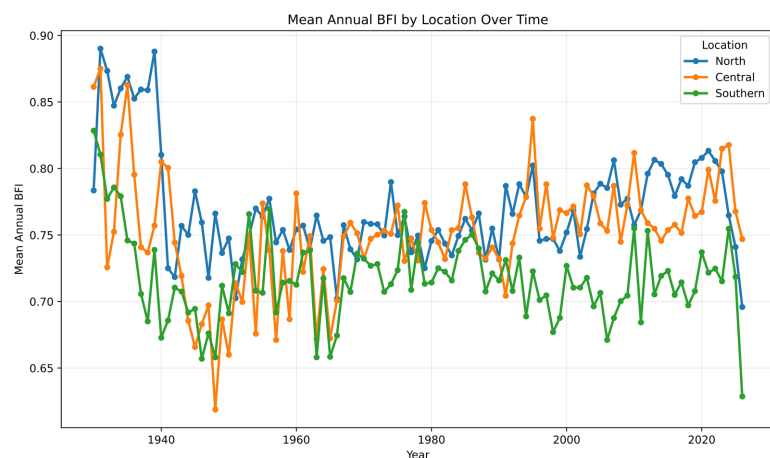


Figure 2. Mean annual baseflow index (BFI) by latitude (Northern $>45.2^\circ$, Central $43.5^\circ - 45.2^\circ$, Southern $<43.5^\circ$) from 1930 to 2026. All regions exhibit interannual and multi-decadal variability, with generally higher and more stable BFI in the northern region, intermediate values in the central region, and lower, more variable BFI in the southern region. Periods of elevated and reduced BFI occur across all regions, though the magnitude and timing of changes differ regionally.

Daily discharge records were screened for completeness prior to analysis. Annual streamflow, annual baseflow, and annual BFI values were computed only for years with sufficient daily observations. Twenty-three stations contained some missing daily observations within their period of record, whereas the remaining stations were complete. Most missing observations occurred in historical portions of long-term records and did not substantially affect annual metrics used in subsequent analyses.

2.2. SPEI Extraction and Processing

Monthly Standardized Precipitation-Evapotranspiration Index (SPEI-12) data were obtained from the SPEIbase dataset in NetCDF format [22] [23]. The SPEI-12, which represents a 12-month accumulation period, captures long-term hydroclimatic variability by integrating precipitation and atmospheric evaporative demand. Data were imported into R as a multilayer raster, and a continuous monthly time vector spanning January 1901 through 2024 was constructed. The dataset was subset to the study period, and each layer was associated with its corresponding calendar year.

Station coordinates were obtained from a CSV file and used to extract SPEI values via bilinear interpolation, providing a continuous monthly time series for each location. Monthly values were aggregated to annual means to align with hydrologic response variables, yielding a single SPEI value per station per year. The resulting dataset was organized into long format and grouped into Northern, Central, and Southern regions based on latitude thresholds. All processing was conducted in R using the *ncdf4* rasters and *tidyverse* packages [24], consistent with current reproducible workflows in hydroclimatic analysis [25].

2.3. Baseflow Separation

Daily streamflow data were obtained from the USGS National Water Information System. Baseflow separation was performed to quantify groundwater contributions to total streamflow. Among available hydrograph separation methods, digital filtering approaches remain the most widely applied in regional and long-term studies due to their objectivity, efficiency, and minimal data requirements [26] [27].

Baseflow was separated using the HYSEP program [28], specifically the local-minimum method with a three-point moving window. This approach identifies local minima in the hydrograph to partition streamflow into baseflow and direct runoff and is appropriate where watershed properties are not well constrained. Although more physically based approaches using environmental tracers or thermal signals can improve process representation, they require high-frequency sampling and site-specific calibration, which limits their applicability for large-sample studies [29]–[32]. The HYSEP method provides a consistent and reproducible approximation, though it does not explicitly distinguish between groundwater and other delayed subsurface contributions such as interflow.

The Baseflow Index (BFI) was then computed for each station-year as the ratio of annual baseflow to annual streamflow:

$$BFI = \frac{\text{Annual Baseflow}}{\text{Annual Streamflow}} \quad (1)$$

2.4. Watershed Delineation

Watersheds were delineated for 73 monitoring stations using the Hydrology toolset in ArcGIS Pro (v. 3.5). Delineation was based on the D8 flow-routing algorithm, which assigns flow direction to the steepest downslope neighbor [33]. A 30-m USGS digital elevation model was first hydrologically conditioned by filling sinks to ensure continuous flow paths. Flow direction and accumulation grids were then derived, and station locations were used as pour points, snapped to high-flow cells to ensure proper alignment with the drainage network [34].

Watershed boundaries were delineated using the Watershed tool and validated against published USGS values, showing agreement within approximately 99%. Although alternative methods such as the D8 algorithm improve representation of divergent flow paths [35], the D8 method was selected due to its computational efficiency and consistent performance in large-sample hydrologic analyses.

2.5. Land Cover Data Processing and Reclassification

Land cover data were obtained from the USGS Annual National Land Cover Database (NLCD) Collection 1.0 for 1985, 2000, 2015, and 2024 [36]. To improve interpretability for hydrologic analysis, detailed NLCD classes were aggregated into broader categories representing hydrologically relevant land cover types. Reclassification was performed using automated scripts in R and verified in ArcGIS Pro to ensure consistency and accuracy.

Land cover rasters were clipped to watershed boundaries using the Extract by Mask tool, producing 296 watershed-specific datasets. The proportional area of each land cover category was calculated, with emphasis on forest, agricultural, and developed land due to their known influence on infiltration, evapotranspiration, and runoff generation [37]. This aggregation preserves key hydrologic contrasts while reducing classification redundancy.

2.6. Correlation Analysis

The Pearson correlation analysis was used to characterize associations between hydroclimatic variability and hydrologic response. Annual SPEI values were paired with corresponding annual baseflow and total streamflow values for each watershed, and correlation coefficients were computed using the `cor()` function in R. Correlation coefficients provide a measure of the strength and direction of linear association between variables based on covariance normalized by variance [38].

Although Pearson correlation assumes linearity and does not capture nonlinear dynamics, it remains a widely used and readily interpretable metric for examining climate-streamflow relationships in large-sample hydrologic studies [39].

Correlation analysis was employed as a descriptive tool to evaluate the degree of correspondence between annual climatic conditions and annual hydrologic metrics rather than as a predictive, explanatory, or causal modeling framework. Land-

cover composition and land-cover change were used to characterize watershed conditions and provide context for interpreting regional and spatial patterns in the correlation results. However, land-cover variables were not incorporated as explanatory variables in a formal statistical model, nor were they evaluated through a dedicated attribution analysis. Consequently, any observed correspondence between land-cover characteristics and climate-streamflow relationships should be interpreted as an association observed within the study dataset rather than as direct evidence that land cover caused the observed hydrologic responses. Differences among regions are therefore discussed in terms of observed patterns and co-occurring watershed characteristics rather than demonstrated cause-and-effect relationships.

Statistical significance was evaluated using an effective sample size adjustment based on lag-1 autocorrelation following Pyper and Peterman [40]. Effective sample sizes were used when calculating confidence intervals and significance estimates for Pearson correlation coefficients.

Correlations were computed using the period of overlap between annual SPEI values and annual discharge-derived metrics at each station. Consequently, sample size varied among stations according to record availability and did not necessarily equal the full length of either the SPEI or discharge record.

3. Results

3.1. Regional Variability in Baseflow Index (BFI)

Mean annual BFI shows clear regional contrasts and pronounced multi-decadal variability (Figure 2). The northern region consistently exhibits the highest values, generally ranging from approximately 0.72 to 0.89, reflecting strong and stable groundwater contributions. In contrast, the southern region displays lower values, typically between approximately 0.65 and 0.77, along with greater variability. The central region falls between these extremes, with BFI commonly ranging from approximately 0.65 to 0.85.

Temporal variability is evident across all regions. During the 1930s, all regions exhibit relatively elevated BFI values, followed by a pronounced decline in the 1940s. In the central region, BFI decreases to values near 0.62 to 0.68 during this period, while the northern region declines to approximately 0.72. The southern region shows similarly strong drying, with several years below 0.70. From the 1950s through the 1980s, variability persists but becomes less extreme in the northern region, where BFI remains relatively stable between 0.73 and 0.78.

Later decades show renewed variability. The central region exhibits a notable increase in the mid-1990s, with values exceeding 0.83, followed by relatively stable conditions through the early 2000s. In the northern region, a gradual increase begins in the early 1990s, with elevated values frequently above 0.80 during the late 2010s and early 2020s. However, a sharp decline occurs after 2024, with values dropping below approximately 0.70 by 2026. The southern region continues to display high variability, with alternating wet and dry periods, culminating in a pronounced decline to approximately 0.63 in 2026, the lowest value observed across the full record.

Across all regions, no consistent long-term increasing or decreasing trend is evident. Instead, the record is characterized by recurring wet and dry cycles, with the magnitude of variability increasing from north to south.

3.2. Regional Patterns in SPEI

SPEI values exhibited broadly similar temporal patterns across the study area (**Figure 3**). Periods of relatively dry and wet conditions generally occurred at the same time in the northern, central, and southern regions, indicating that watersheds were responding to a common regional climate signal. Notable dry periods were evident during the 1930s and 1950s, while wetter conditions occurred during portions of the early twentieth century, the 1960s, and parts of the early twenty-first century.

Although the timing of major wet and dry periods was similar among regions, differences in the magnitude of annual SPEI values were observed. Northern watersheds generally exhibited less negative average SPEI values and larger year-to-year fluctuations. Following approximately 1980, the northern region also experienced more frequent positive SPEI values and several extended periods of above-average moisture conditions relative to earlier decades. Central watersheds showed intermediate behavior, with periods of both positive and negative SPEI but less pronounced shifts through time. In contrast, southern watersheds tended to exhibit more negative annual SPEI values and more frequent runs of below-average conditions. After approximately 1980, the southern region showed a tendency toward more frequent negative SPEI values and longer periods of below-average moisture conditions relative to the northern region. However, these observations should be interpreted descriptively because the analysis was not designed to formally test regional differences in SPEI distributions, persistence, or long-term trends.

Figure 4 shows the spatial relationship of the Pearson correlation coefficient (r). The figure indicates considerable variability across monitoring locations. The strongest positive correlations are concentrated in the central portion of the study area, particularly between approximately 45° and 47° N latitude, where several sites exhibit moderately strong to strong positive relationships ($r > 0.5$). In contrast, the strongest negative correlations are also found within portions of the central region, with isolated sites near 43° N latitude displaying correlation coefficients below -0.5 . Northern and southern sites generally exhibit weaker or mixed correlations, with many locations showing values near zero.

Overall, the SPEI analysis indicates that all study regions experienced similar broad-scale climatic variability over time, while the magnitude and expression of annual climatic anomalies varied among regions. Consequently, subsequent analyses focus on contemporaneous associations between annual SPEI and annual hydrologic metrics rather than on causal attribution or formal evaluation of long-term regional climatic differences.

3.3. Land Cover Distribution and Change

Land-cover composition differed substantially among the northern, central, and

southern regions, and the magnitude of land-cover change varied across the study area (**Figures 5-6**). These land-cover data were used to characterize watershed conditions and provide context for subsequent comparisons of climate-streamflow associations.

As shown in **Figure 7**, the northern region was dominated by forest cover throughout the period of analysis. Forested land remained consistently high, with only minor changes between 1985 and 2024. Agricultural land comprised a relatively small proportion of the landscape and exhibited little change through time. Developed land increased slightly, particularly after 2000, although changes were generally modest, typically remaining below three percent of watershed area.

The central region exhibited a more mixed land-cover composition. Agriculture represented the largest land-cover class but generally declined between 1985 and 2024. Reductions were observed across many watersheds and commonly ranged from approximately two to five percent, with larger decreases occurring in some locations. Developed land increased throughout the region, while forest cover remained comparatively stable with only localized changes.

The southern region exhibited the largest observed changes in land-cover composition. Agricultural land decreased across many watersheds, often exceeding five percent and in some cases exceeding fifteen percent of watershed area. Developed land showed the largest increases observed in the study, with several watersheds experiencing gains greater than five percent and occasionally exceeding fifteen percent. Forest cover remained a relatively small component of the landscape and generally changed little over the analysis period.

Overall, the magnitude and spatial extent of land-cover change increased from north to south. These regional differences provide a descriptive characterization of watershed conditions across the study area and establish context for interpreting regional variations in climate-streamflow associations. Because land-cover variables were not incorporated into a formal attribution or predictive modeling framework, these observations are presented as watershed characteristics rather than evidence of land-cover effects on hydrologic response.

3.4. Spatial Variability in SPEI-BFI Correlation

The distribution of correlations between annual SPEI and annual hydrologic metrics differed among watershed-size classes (**Figures 8-10**). These correlations describe contemporaneous associations between annual climatic conditions and annual streamflow metrics during the period of overlapping record for each station.

Large watersheds generally exhibited higher correlation coefficients and lower variability than smaller watershed classes across all regions. Median correlations commonly ranged from approximately 0.72 to 0.78 for both annual baseflow and annual streamflow, and interquartile ranges were comparatively narrow.

Medium-sized watersheds exhibited slightly lower median correlations, typically ranging from approximately 0.68 to 0.71. Variability increased relative to the large-watershed class, particularly for baseflow correlations. This pattern was most evident in the southern region, where correlation coefficients spanned a wider

range of values than observed for total streamflow.

Small watersheds exhibited the greatest dispersion of correlation coefficients. In the southern region, median baseflow correlations were generally lower, ranging from approximately 0.52 to 0.54, and displayed substantial variability among watersheds. Corresponding correlations with total streamflow were somewhat higher, typically ranging from approximately 0.63 to 0.65. In contrast, small watersheds in the northern and central regions generally exhibited higher baseflow correlations, commonly between approximately 0.64 and 0.66, with correspondingly lower variability. Total streamflow correlations in these regions were slightly higher, generally ranging from approximately 0.68 to 0.70.

3.5. Watershed Size and SPEI-Streamflow

Correlations between annual SPEI and annual streamflow metrics differed among watershed-size classes (**Figures 8-10**). The results summarize contemporaneous associations between annual climatic conditions and annual hydrologic metrics over the period of overlapping record available for each watershed.

Large watersheds generally exhibited higher correlation coefficients and less variability than smaller watershed classes across all regions. Median correlation values commonly ranged from approximately 0.72 to 0.78 for both annual baseflow and annual streamflow, with relatively narrow interquartile ranges indicating a comparatively consistent distribution of correlation values among watersheds in this size class.

In medium-sized watersheds, median correlation coefficients were slightly lower, generally ranging from approximately 0.68 to 0.71. Variability increased relative to the large-watershed group, particularly for annual baseflow. Within the southern region, baseflow correlations spanned a broader range of values than total streamflow correlations, although substantial overlap remained among watersheds.

Small watersheds exhibited the broadest distribution of correlation coefficients. In the southern region, median baseflow correlations generally ranged from approximately 0.52 to 0.54 and displayed considerable variability among watersheds. Correlations between SPEI and annual streamflow were somewhat higher, typically ranging from approximately 0.63 to 0.65. In contrast, small watersheds in the northern and central regions generally exhibited higher baseflow correlation coefficients, commonly ranging from approximately 0.64 to 0.66, with less variability than observed in the southern region. Correlations with annual streamflow were slightly higher, typically ranging from approximately 0.68 to 0.70.

3.6. Observation of Regional Patterns

Several broad regional patterns were evident across the study area. Northern watersheds were generally characterized by higher annual BFI values, predominantly forested land cover, and comparatively weak but spatially consistent correlations between annual SPEI and annual BFI. Central watersheds exhibited intermediate BFI values, mixed land-cover characteristics, and a geographically concentrated area of moderate positive SPEI-BFI correlations. Southern watersheds displayed

lower BFI values, greater land-cover change, and a wider range of observed correlation coefficients, resulting in more spatially heterogeneous correlation patterns.

Although annual SPEI exhibited similar broad temporal variability across all three regions, the observed associations between annual SPEI and hydrologic metrics differed among watersheds. Larger watersheds generally exhibited less variability in correlation coefficients, whereas smaller watersheds exhibited a broader range of observed correlation values, particularly in the southern region. Similarly, the northern region tended to display more spatially consistent correlations than the southern region.

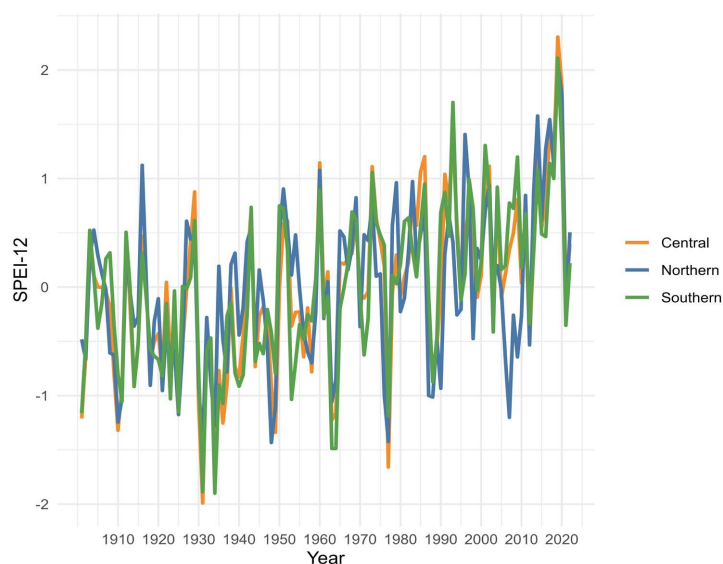


Figure 3. Mean annual Standardized Precipitation-Evapotranspiration Index (SPEI) by region (Northern $>45.2^\circ$, Central $43.5^\circ - 45.2^\circ$, Southern $<43.5^\circ$) from 1901 to 2022. All regions exhibit synchronous multi-decadal variability, with shared wet periods (positive SPEI) and dry periods (negative SPEI) across the record. Differences among regions are primarily reflected in the magnitude of extremes and short-term variability rather than timing, indicating broadly consistent regional climate forcing.

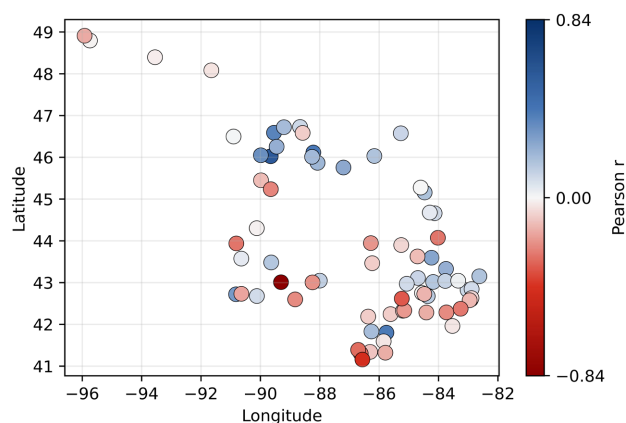


Figure 4. Spatial distribution of Pearson correlation (r) between BFI and SPEI. Positive correlations (blue) cluster in the central region, while the southern region shows mixed positive and negative values and the northern region exhibits generally weak correlations.

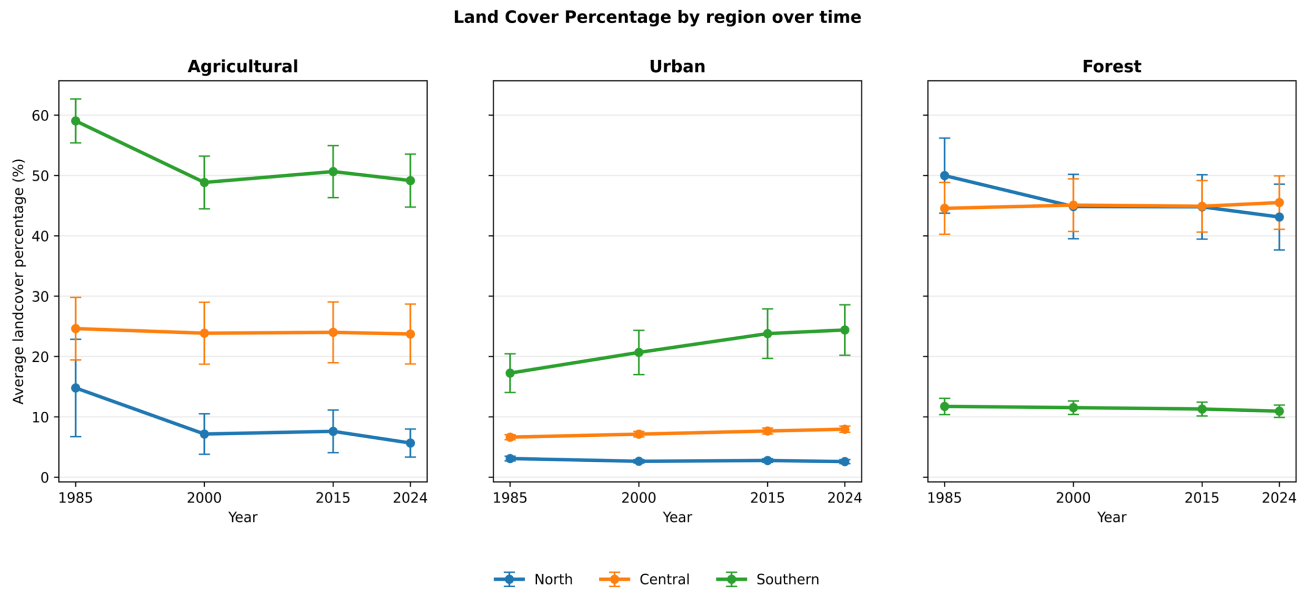


Figure 5. Mean percent agriculture, developed, and forest land cover by region (North, Central, South) from 1985-2024, with each panel showing regional trends over time.

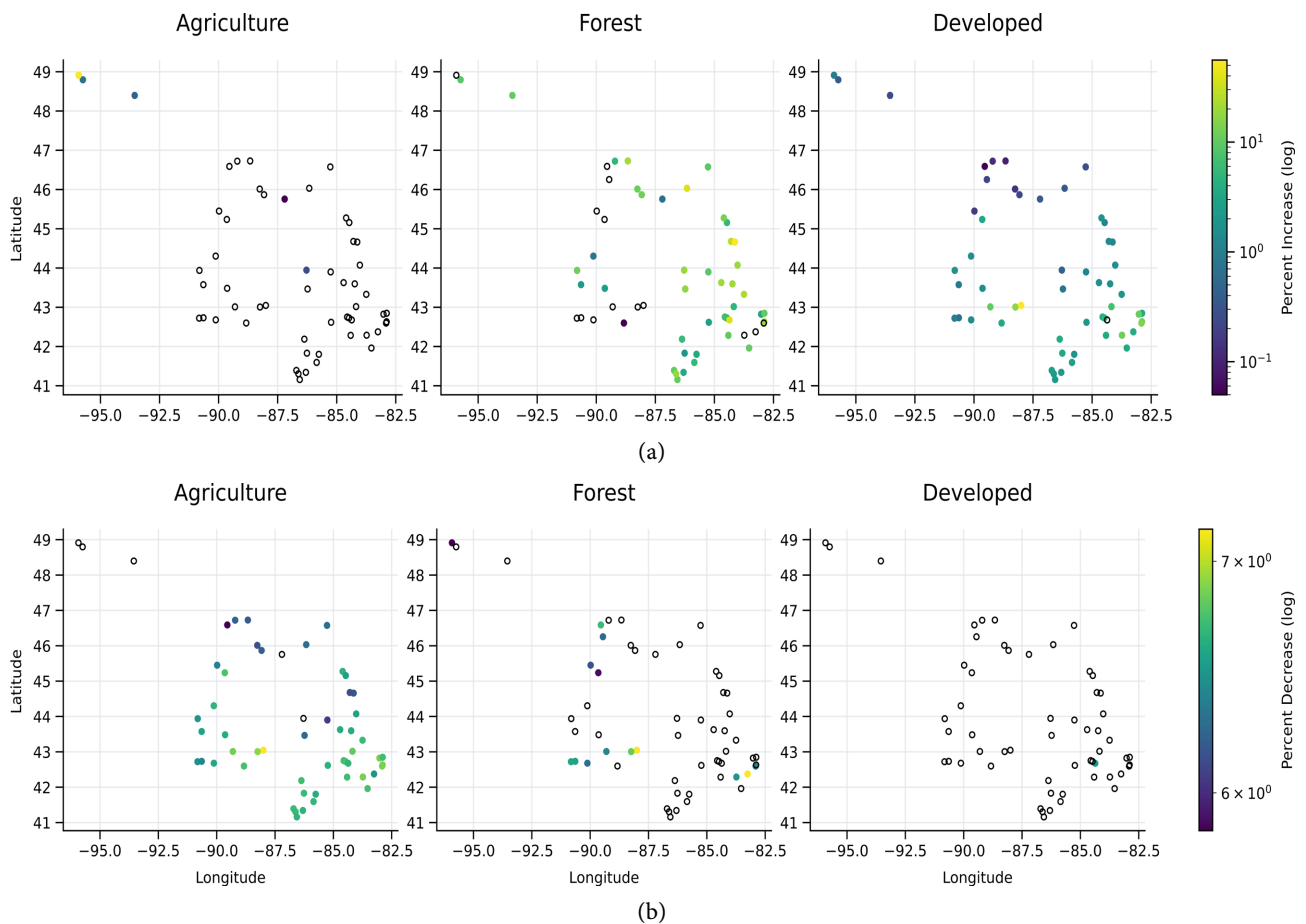


Figure 6. (a) shows mean percent land cover increases for agriculture, developed, and forest classes across the Northern, Central, and Southern regions for the years 1985, 2000, 2015, and 2024. (b) shows mean percent land cover decreases for agriculture, developed, and forest classes across the Northern, Central, and Southern regions for the years 1985, 2000, 2015, and 2024.

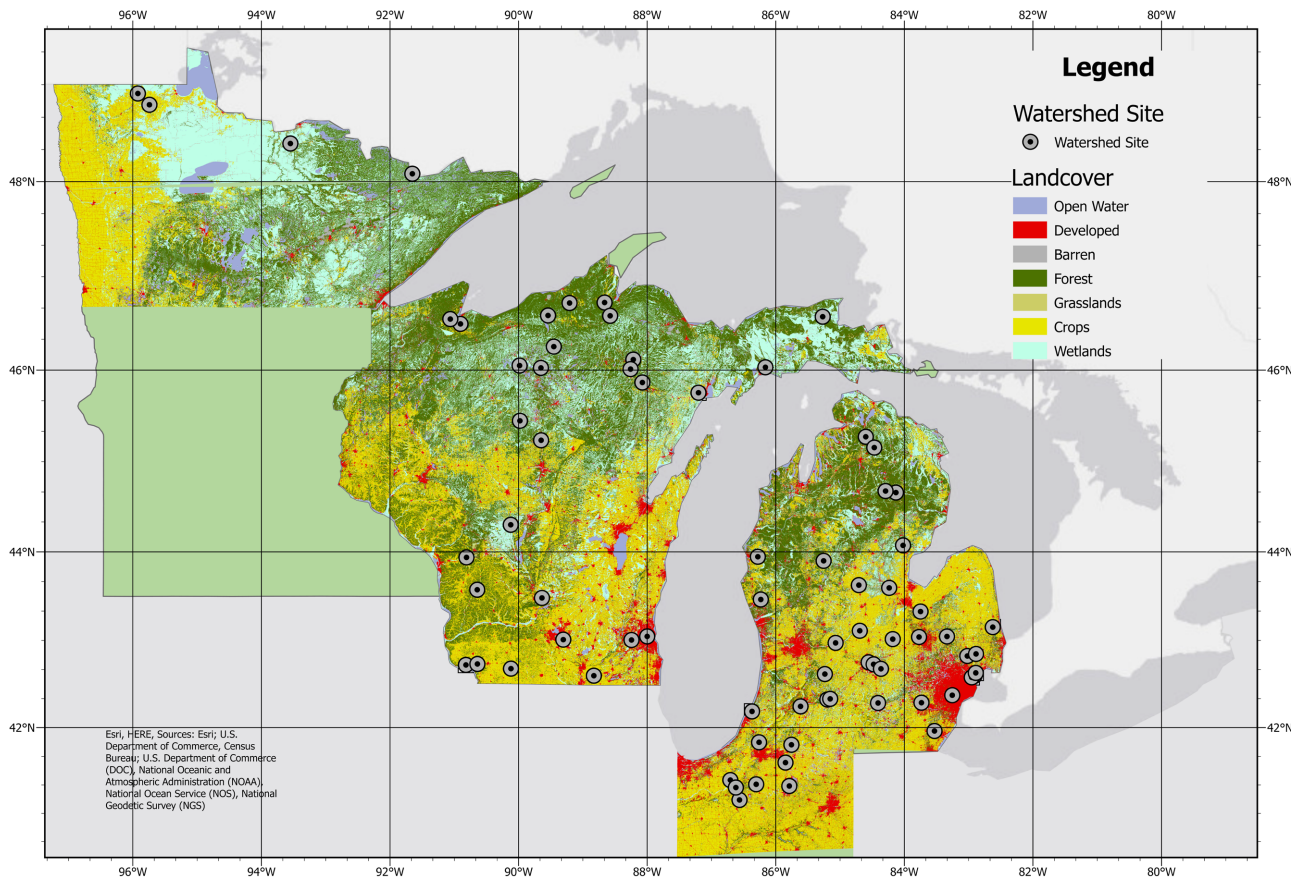


Figure 7. Landcover map of the study region from 2024. Forests dominate the northern portion. The central region has agricultural in the central region, and the southern region has a combination of agriculture and urban.

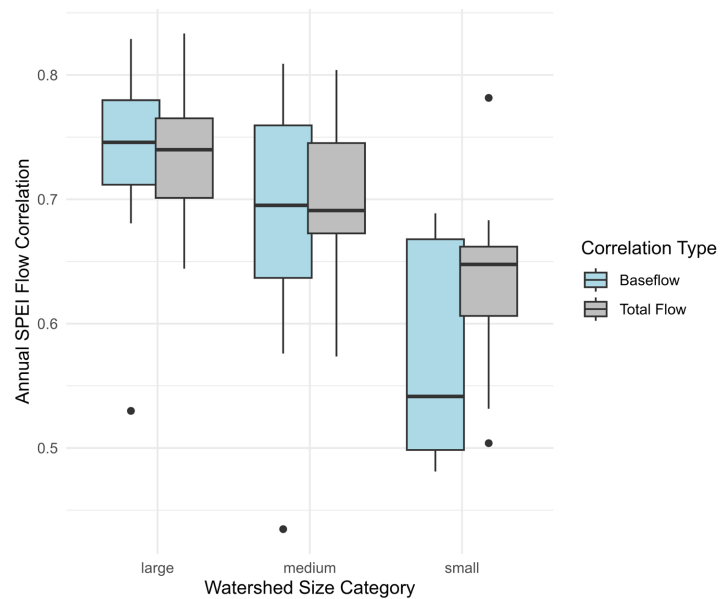


Figure 8. Boxplots of Pearson correlation between annual SPEI and streamflow (baseflow and total flow) by watershed size category (large, medium, small). Correlation strength decreases and variability increases with decreasing watershed size, with the largest divergence between baseflow and total flow observed in small watersheds.

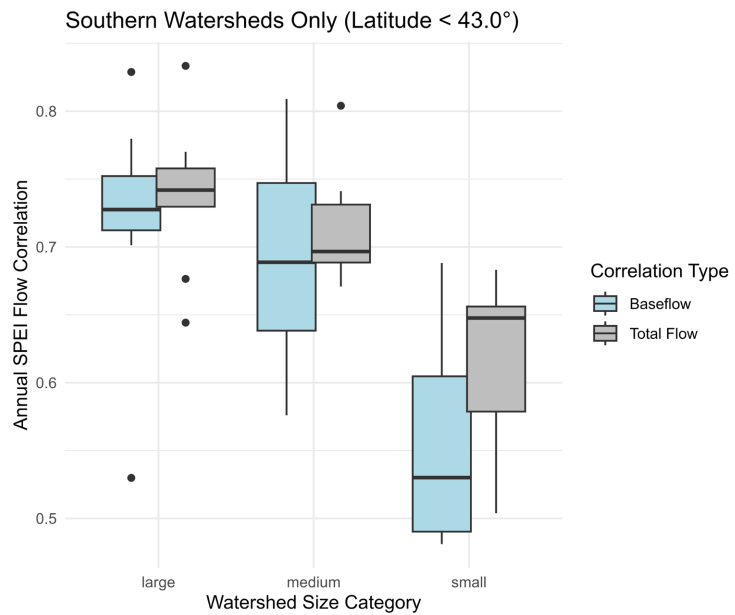


Figure 9. Boxplots of Pearson correlation between annual SPEI and streamflow (baseflow and total flow) for **southern region watersheds**, grouped by watershed size (large, medium, small). Correlation strength decreases and variability increases with decreasing watershed size, with the greatest separation between baseflow and total flow observed in small watersheds.

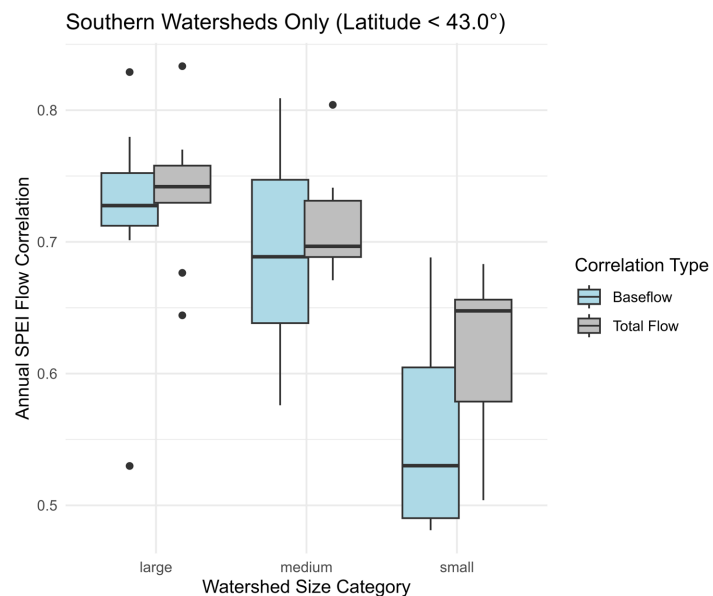


Figure 10. Boxplots of Pearson correlation between annual SPEI and streamflow (baseflow and total flow) for **northern and central region watersheds**, grouped by watershed size (large, medium, small). Correlations are strongest in large watersheds and decrease slightly with size, with modest increases in variability for medium and small watersheds.

4. Discussion

4.1. Regional Variability in Baseflow Response

Regional differences in annual BFI were evident throughout the study period (**Fig-**

ure 2). Although all regions exhibited substantial interannual and multi-decadal variability, the magnitude and stability of BFI differed among regions. Northern watersheds generally exhibited higher annual BFI values and lower variability, whereas southern watersheds exhibited lower BFI values and greater year-to-year fluctuations. Central watersheds displayed intermediate conditions.

These regional differences occurred alongside differences in watershed characteristics, including land-cover composition, land-cover change, watershed size distribution, and hydrogeologic setting. Northern watersheds were more commonly characterized by extensive forest cover and relatively limited land-cover change, whereas southern watersheds generally exhibited greater agricultural and developed land cover and larger changes through time. The observed BFI patterns are therefore consistent with regional variation in watershed characteristics documented in previous studies of the Upper Midwest [3] [4].

Because baseflow reflects groundwater contributions to streamflow, differences in BFI may be associated with variation in watershed storage, subsurface connectivity, infiltration characteristics, and other physical watershed attributes. However, the analyses presented here were not designed to isolate or quantify the independent effects of these factors. Consequently, the observed regional differences should be interpreted as descriptive patterns rather than evidence of specific causal mechanisms.

No consistent long-term increasing or decreasing trend was evident across all regions. Instead, the records were characterized by alternating periods of relatively high and low BFI that broadly coincided with regional wet and dry climatic periods. This pattern suggests that both climatic variability and watershed characteristics may contribute to observed differences in baseflow behavior, although the present analysis does not distinguish the relative importance of these influences. As a result, the discussion focuses on observed associations between climatic variability and hydrologic metrics rather than causal attribution [10] [14].

4.2. Regional Climatic Variability and Hydrologic Context

SPEI values exhibited broadly similar temporal patterns across the study area, with dry and wet periods generally occurring at comparable times in the northern, central, and southern regions (Figure 3). This temporal coherence indicates that watersheds throughout the study area experienced a common regional climatic signal. Major droughts during the 1930s and 1950s and wetter periods during portions of the early twentieth century, the 1960s, and the early twenty-first century were evident across all regions.

Although the timing of major climatic fluctuations was broadly similar, differences in the magnitude and expression of annual SPEI values were observed among regions. Northern watersheds generally exhibited less negative annual SPEI values and greater year-to-year variability. Following approximately 1980, positive SPEI values became more common in the northern region, resulting in several extended periods characterized by above-average moisture conditions. Central watersheds

displayed intermediate behavior, with alternating wet and dry periods but less pronounced changes through time. Southern watersheds generally exhibited more negative annual SPEI values and more frequent sequences of below-average conditions. After approximately 1980, negative SPEI values occurred more frequently in the southern region than in the northern region, corresponding to longer periods of below-average climatic water balance.

These regional differences provide important context for interpreting observed hydrologic patterns. However, SPEI represents climatic water balance and does not directly account for watershed storage, groundwater contributions, stream-flow generation processes, or potential lagged responses within hydrologic systems. Consequently, differences between SPEI and hydrologic metrics observed among regions should be interpreted as differences in contemporaneous associations rather than evidence of specific watershed mechanisms.

Taken together, the SPEI results may indicate that all regions were subject to similar large-scale climatic variability, while the magnitude of annual climatic anomalies varied across the study area. Therefore, subsequent comparisons focus on how annual hydrologic metrics corresponded with annual SPEI during overlapping periods of record rather than on causal attribution of regional hydrologic differences.

4.3. Regional Land-Cover Patterns and Hydrologic Context

Land-cover composition and land-cover change varied substantially among regions (**Figures 5-6**) and provide important context for interpreting the observed hydrologic patterns. Northern watersheds were characterized by extensive forest cover and relatively limited land-cover change over the study period. These watersheds also generally exhibited higher and less variable BFI values. In contrast, southern watersheds experienced larger changes in land-cover composition, including substantial increases in developed land and decreases in agricultural land, and were characterized by lower BFI values and greater variability. Central watersheds exhibited intermediate conditions in both land-cover characteristics and hydrologic metrics.

The observed correspondence between regional land-cover patterns and hydrologic characteristics is consistent with findings from previous studies that have linked differences in infiltration, evapotranspiration, groundwater recharge, and runoff generation to variations in land use and land cover [15] [37] [41]. Forested watersheds are often associated with greater infiltration opportunities and stronger groundwater contributions, whereas developed and intensively managed landscapes may exhibit different flow pathways and altered runoff characteristics. However, the analyses presented here were not designed to quantify the independent effects of land cover or land-cover change on streamflow metrics.

The central region represents an intermediate landscape setting, characterized by mixed land-cover composition and moderate land-cover change. This region also exhibited intermediate hydrologic characteristics relative to the northern and

southern regions. Previous studies have documented changes in hydrologic behavior associated with land-use transitions across the Midwest [9], although the present analysis does not directly evaluate those relationships.

Consequently, land-cover characteristics are discussed here as descriptive watershed attributes that co-occur with observed differences in BFI and climate-streamflow associations. While the regional patterns are consistent with mechanisms proposed in previous hydrologic studies, the results should be interpreted as observational associations rather than evidence of direct land-cover effects on hydrologic response.

4.4. Regional Patterns in SPEI-BFI Associations

Spatial patterns in the correlations between annual SPEI and annual BFI provide additional insight into regional variability in observed climate-hydrologic associations (Figure 3). Correlation coefficients varied among watersheds and regions, indicating that the correspondence between annual climatic conditions and annual BFI was not spatially uniform across the study area.

In the northern region, correlation coefficients were generally weak and clustered near zero. Correlation values also exhibited relatively little spatial variation, resulting in a geographically consistent pattern of weak contemporaneous association between annual SPEI and annual BFI.

The central region contained a geographically concentrated area of moderate positive correlations, with several watersheds exhibiting correlation coefficients between approximately 0.4 and 0.8. Outside of this area, weaker associations were more common. This pattern suggests that the strength of observed SPEI-BFI associations varied within the region rather than occurring uniformly across all watersheds.

The southern region exhibited the greatest spatial heterogeneity. Correlation coefficients ranged from strongly negative to moderately positive, and neighboring watersheds often displayed substantially different relationships. As a result, the spatial distribution of correlations was less uniform than that observed in either the northern or central regions.

These regional patterns demonstrate that the magnitude and direction of contemporaneous SPEI-BFI associations differed among watersheds despite the broadly similar climatic variability identified in the SPEI record. However, because the analysis was based on pairwise correlations and did not include formal testing of watershed attributes, land-cover characteristics, hydrogeologic conditions, or other explanatory variables, the results should be interpreted as descriptive spatial patterns rather than evidence of specific mechanisms. Consequently, the observed differences identify regions where annual BFI exhibited stronger or weaker correspondence with annual SPEI during the period of overlapping record but do not establish the causes of those differences.

4.5. Watershed Size and Climate-Streamflow Associations

Differences in SPEI-streamflow correlations were observed among watershed-size

classes (**Figures 7-9**). Larger watersheds generally exhibited higher correlation coefficients and less variability than smaller watersheds. Median correlations for both annual baseflow and annual streamflow were commonly between approximately 0.72 and 0.78, with relatively narrow interquartile ranges.

Medium-sized watersheds exhibited somewhat lower correlation coefficients and greater variability. Median values generally ranged from approximately 0.68 to 0.71, although the distribution of correlations varied among regions and between hydrologic metrics. In the southern region, baseflow correlations displayed a broader range of values than total streamflow correlations.

Small watersheds exhibited the widest range of correlation coefficients. This pattern was particularly evident in the southern region, where baseflow correlations were generally lower and more variable than those observed in the northern and central regions. Correlations between SPEI and total streamflow also varied substantially among small watersheds, although median values were generally higher than those observed for baseflow. In contrast, small watersheds in the northern and central regions tended to exhibit higher correlations and narrower distributions.

The observed differences among watershed-size classes are consistent with previous studies reporting greater hydrologic variability and more complex responses in smaller basins relative to larger drainage networks [4] [5]. Larger watersheds integrate hydrologic processes over broader spatial extents, whereas smaller watersheds may be more sensitive to local watershed conditions and short-term variability [4] [5].

However, the present analysis was designed to evaluate contemporaneous associations between annual SPEI and annual hydrologic metrics rather than to identify causal controls on correlation strength. Watershed size was used as a classification variable for comparison among groups and was not incorporated within a formal attribution framework. Consequently, the observed differences among size classes should be interpreted as descriptive patterns within the dataset rather than evidence that watershed size directly determines climate-streamflow relationships. The results indicate that the magnitude and variability of SPEI-streamflow associations differed among watershed groups, while the causes of those differences were not explicitly evaluated in this study.

Taken together, the results indicate that broad climatic variability was similar across the study area, while the observed relationships between annual SPEI and hydrologic metrics varied among watersheds. All three regions experienced comparable periods of wet and dry climatic conditions, yet differences were evident in annual BFI values, land-cover characteristics, watershed-size distributions, and the magnitude and direction of SPEI-hydrologic correlations.

The northern region was characterized by relatively high BFI values, extensive forest cover, limited land-cover change, and generally weak but spatially consistent associations between annual SPEI and annual BFI. The central region exhibited intermediate conditions, including mixed land-cover characteristics and a

geographically concentrated area of moderate positive SPEI-BFI correlations. The southern region was characterized by lower BFI values, greater land-cover change, and the widest range of observed correlation coefficients, resulting in more spatially heterogeneous patterns.

Differences were also observed among watershed-size classes. Larger watersheds generally exhibited less variability in correlation coefficients, while smaller watersheds exhibited broader distributions of observed correlations, particularly within the southern region. These findings indicate that the strength and consistency of contemporaneous SPEI-streamflow associations were not uniform across the study area.

Collectively, the results suggest that climatic variability alone does not fully describe the range of observed hydrologic responses among watersheds. Differences in climate-streamflow associations frequently coincided with differences in watershed characteristics, including land-cover composition, land-cover change, watershed size, and regional setting.

5. Conclusions

This study demonstrates that hydrologic responses across the upper Midwest are not uniform despite the presence of a broadly coherent regional climate signal as represented by SPEI. Although major wet and dry periods occurred across all regions, annual baseflow, BFI, and climate-streamflow associations varied substantially among watersheds. Northern watersheds, characterized by relatively stable forest cover and limited land-cover change, generally exhibited higher and less variable BFI values and comparatively consistent, although often weaker, correlations with SPEI. In contrast, southern watersheds exhibited lower BFI values, greater variability, larger land-cover changes, and a wider range of observed SPEI-streamflow associations. The central region displayed intermediate conditions and included localized areas of relatively strong correlations between SPEI and hydrologic metrics.

Differences were also observed among watershed-size classes. Larger watersheds generally exhibited higher and less variable correlation coefficients, whereas smaller watersheds displayed a broader range of observed relationships, particularly within the southern region. These patterns indicate that the magnitude and consistency of contemporaneous associations between annual SPEI and annual hydrologic metrics varied across watershed groups and regions.

Taken together, the results indicate that similar regional climatic variability can be associated with different hydrologic responses across watersheds. Differences in BFI, land-cover composition, land-cover change, watershed size, and SPEI-streamflow correlations frequently occurred together across the study area. However, because land-cover variables and watershed characteristics were not incorporated into a formal attribution framework, the analyses cannot determine the relative contributions of individual factors to the observed patterns. Consequently, the findings should be interpreted as evidence of spatial variation in climate-

streamflow associations rather than as direct evidence that specific watershed characteristics caused the observed hydrologic responses.

The results further suggest that climatic indices alone do not fully characterize the range of hydrologic responses observed among watersheds. Incorporating watershed characteristics alongside climatic information may improve understanding of regional hydrologic variability and provide additional context for interpreting climate-streamflow relationships across the upper Midwest. Future studies that explicitly evaluate land-cover, hydrogeologic, and watershed-scale controls using formal attribution or multivariate modeling approaches may help clarify the mechanisms underlying the spatial patterns identified in this study.

Author Contributions

Brooke Payne performed landcover analysis, watershed delineation, statistical analysis of landcover with hydrologic variables, and helped write the introduction and results; Molly Wells performed landcover analysis and statistical analysis of landcover with hydrologic variables, and helped write the introduction and results. Katherine Clancy designed the project, selected sites, helped write code to do land-cover analyses, and performed all other statistical analyses, edited the paper and wrote the results, discussion, conclusion and abstract. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Xiao, F.Y., Wang, X.M. and Fu, C.S. (2023) Impacts of Land Use/Land Cover and Climate Change on Hydrological Cycle in the Xiaoxingkai Lake Basin. *Journal of Hydrology: Regional Studies*, **47**, Article ID: 101422. <https://doi.org/10.1016/j.ejrh.2023.101422>
- [2] Kraft, G.J., Clancy, K., Mechenich, D.J. and Haucke, J. (2011) Irrigation Effects in the Northern Lake States: Wisconsin Central Sands Revisited. *Groundwater*, **50**, 308-318. <https://doi.org/10.1111/j.1745-6584.2011.00836.x>
- [3] Ayers, J.R., Villarini, G., Schilling, K., Jones, C., Brookfield, A., Zipper, S.C., *et al.* (2022) The Role of Climate in Monthly Baseflow Changes across the Continental United States. *Journal of Hydrologic Engineering*, **27**, Article ID: 04022006. [https://doi.org/10.1061/\(asce\)he.1943-5584.0002170](https://doi.org/10.1061/(asce)he.1943-5584.0002170)
- [4] Price, K. (2011) Effects of Watershed Topography, Soils, Land Use, and Climate on Baseflow Hydrology in Humid Regions: A Review. *Progress in Physical Geography: Earth and Environment*, **35**, 465-492. <https://doi.org/10.1177/0309133311402714>
- [5] Addor, Newman, A., Mizukami, M. and Clark, M.P. (2017) Catchment Attributes for Large-Sample Studies. UCAR/NCAR.
- [6] Ramankutty, N. and Foley, J.A. (1999) Estimating Historical Changes in Global Land Cover: Croplands from 1700 to 1992. *Global Biogeochemical Cycles*, **13**, 997-1027. <https://doi.org/10.1029/1999gb900046>
- [7] Mueller, N.D., Butler, E.E., McKinnon, K.A., Rhines, A., Tingley, M., Holbrook,

- N.M., *et al.* (2016) Cooling of US Midwest Summer Temperature Extremes from Cropland Intensification. *Nature Climate Change*, **6**, 317-322. <https://doi.org/10.1038/nclimate2825>
- [8] Twine, T.E., Kucharik, C.J. and Foley, J.A. (2004) Effects of Land Cover Change on the Climate of the Central United States. *Journal of Climate*, **17**, 292-305.
- [9] Nocco, M.A., Smail, R.A. and Kucharik, C.J. (2019) Observation of Irrigation-Induced Climate Change in the Midwest United States. *Global Change Biology*, **25**, 3472-3484. <https://doi.org/10.1111/gcb.14725>
- [10] Zhang, Y.K. and Schilling, K.E. (2006) Increasing Streamflow and Baseflow in Mississippi River since the 1940s: Effect of Land Use Change. *Journal of Hydrology*, **324**, 412-422. <https://doi.org/10.1016/j.jhydrol.2005.09.033>
- [11] Schilling, K.E. and Libra, R.D. (2003) Increased Baseflow in Iowa over the Second Half of the 20th Century. *JAWRA Journal of the American Water Resources Association*, **39**, 851-860. <https://doi.org/10.1111/j.1752-1688.2003.tb04410.x>
- [12] Valayamkunnath, P., Barlage, M., Chen, F., Gochis, D.J. and Franz, K.J. (2020) Mapping of 30-Meter Resolution Tile-Drained Croplands Using a Geospatial Modeling Approach. *Scientific Data*, **7**, Article No. 257. <https://doi.org/10.1038/s41597-020-00596-x>
- [13] Ahiablame, L., Sinha, T., Paul, M., Ji, J. and Rajib, A. (2017) Streamflow Response to Potential Land Use and Climate Changes in the James River Watershed, Upper Midwest United States. *Journal of Hydrology: Regional Studies*, **14**, 150-166. <https://doi.org/10.1016/j.ejrh.2017.11.004>
- [14] Ficklin, D.L., Robeson, S.M. and Knouft, J.H. (2016) Impacts of Recent Climate Change on Trends in Baseflow and Stormflow in United States Watersheds: U.S. Baseflow and Stormflow Trends. *Geophysical Research Letters*, **43**, 5079-5088. <https://doi.org/10.1002/2016gl069121>
- [15] Lerner, D.N. (2002) Identifying and Quantifying Urban Recharge: A Review. *Hydrogeology Journal*, **10**, 143-152. <https://doi.org/10.1007/s10040-001-0177-1>
- [16] Li, C., Sun, G., Caldwell, P.V., Cohen, E., Fang, Y., Zhang, Y., *et al.* (2020) Impacts of Urbanization on Watershed Water Balances across the Conterminous United States. *Water Resources Research*, **56**, e2019WR026574. <https://doi.org/10.1029/2019wr026574>
- [17] Bhaskar, A.S., Hogan, D.M. and Archfield, S.A. (2016) Urban Base Flow with Low Impact Development. *Hydrological Processes*, **30**, 3156-3171. <https://doi.org/10.1002/hyp.10808>
- [18] Slater, L. and Villarini, G. (2017) Evaluating the Drivers of Seasonal Streamflow in the U.S. Midwest. *Water*, **9**, Article No. 695. <https://doi.org/10.3390/w9090695>
- [19] Clancy, K.A. (2023) Standardized Baseflow Drought Index Comparison to SPEI in High Baseflow Streams. *Journal of Water Resource and Protection*, **15**, 557-580. <https://doi.org/10.4236/jwarp.2023.1511031>
- [20] Clancy, K. and Payne, B. (2025) Seasonal and Regional Variability in Hydrological and Drought Responses in the Great Lakes Region: Impacts of SPEI Data Window Selection on Trend Detection. *Open Journal of Modern Hydrology*, **15**, 269-293. <https://doi.org/10.4236/ojmh.2025.154017>
- [21] Singh, V.P. and Woolhiser, D.A. (2002) Mathematical Modeling of Watershed Hydrology. *Journal of Hydrologic Engineering*, **7**, 270-292. [https://doi.org/10.1061/\(asce\)1084-0699\(2002\)7:4\(270\)](https://doi.org/10.1061/(asce)1084-0699(2002)7:4(270))
- [22] Vicente-Serrano, S.M., Beguería, S. and López-Moreno, J.I. (2010) A Multiscalar

- Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate*, **23**, 1696-1718.
<https://doi.org/10.1175/2009jcli2909.1>
- [23] Beguería, S., Vicente-Serrano, S.M., Reig, F. and Latorre, B. (2014) Standardized Precipitation Evapotranspiration Index (SPEI) Revisited: Parameter Fitting, Evapotranspiration Models, Tools, Datasets and Drought Monitoring. *International Journal of Climatology*, **34**, 3001-3023. <https://doi.org/10.1002/joc.3887>
- [24] Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., et al. (2019) Welcome to the Tidyverse. *Journal of Open Source Software*, **4**, Article No. 1686. <https://doi.org/10.21105/joss.01686>
- [25] Panchanathan, A., Ahrari, A., Ghag, K.S., Mustafa, S., Haghighi, A.T., Kløve, B., et al. (2024) An Overview of Approaches for Reducing Uncertainties in Hydrological Forecasting: Progress and Challenges. *Earth-Science Reviews*, **258**, Article ID: 104956. <https://doi.org/10.1016/j.earscirev.2024.104956>
- [26] Eckhardt, K. (2005) How to Construct Recursive Digital Filters for Baseflow Separation. *Hydrological Processes*, **19**, 507-515. <https://doi.org/10.1002/hyp.5675>
- [27] Xie, Z., et al. (2020) Evaluation of Baseflow Separation Methods across Diverse Hydrological Regimes. *Journal of Hydrology*, **585**, Article ID: 124728.
- [28] Sloto, R.A. and Crouse, M.Y. (1996) HYSEP: A Computer Program for Streamflow Hydrograph Separation. USGS Water-Resources Investigations Report, 96-4040.
- [29] Klaus, J. and McDonnell, J.J. (2013) Hydrograph Separation Using Stable Isotopes: Review and Evaluation. *Journal of Hydrology*, **505**, 47-64. <https://doi.org/10.1016/j.jhydrol.2013.09.006>
- [30] Kirchner, J.W. (2016) Aggregation in Environmental Systems. *Water Resources Research*, **52**, 3417-3437.
- [31] Schmidt, C., Lewandowski, J., Galloway, J.N., Chalari, A., Ciocca, F., Krause, S., Pfister, L. and Antonelli, M. (2024) Heat as a Hydrological Tracer. In: Krause, S., Hannah, D.M. and Grimm, N.B., Eds., *Ecohydrological Interfaces*, Wiley, 167-189.
- [32] Schilling, O.S., Halloran, L.J.S., Delottier, H., Sano, Y. and Therrien, R. (2023) Editorial: Advances and Emerging Methods in Tracer Hydrogeology. *Frontiers in Water*, **5**, Article ID: 1243114. <https://doi.org/10.3389/frwa.2023.1243114>
- [33] Jenson, S. (1984) Automated Derivation of Hydrological Basin Characteristics from Digital Elevation Data. US Geological Survey Report 14-08-0001-20129. <https://cartogis.org/docs/proceedings/archive/auto-carto-7/pdf/automated-derivation-of-hydrologic-basin-characteristics-from-digital-elevation-model-data.pdf>
- [34] Tarboton, D.G. (1997) A New Method for the Determination of Flow Directions and Upslope Areas in Grid Digital Elevation Models. *Water Resources Research*, **33**, 309-319. <https://doi.org/10.1029/96wr03137>
- [35] U.S. Geological Survey (2024) 1 Arc-Second Digital Elevation Models (DEMs)—USGS National Map 3D Elevation Program (3DEP) Downloadable Data Collection. U.S. Geological Survey. <https://www.usgs.gov/3d-elevation-program>
- [36] U.S. Geological Survey (2024) Annual NLCD Collection 1 Science Products. <https://www.usgs.gov/centers/eros/science/annual-national-land-cover-database>
- [37] Banjara, M., Bhusal, A., Ghimire, A.B. and Kalra, A. (2024) Impact of Land Use and Land Cover Change on Hydrological Processes in Urban Watersheds: Analysis and Forecasting for Flood Risk Management. *Geosciences*, **14**, Article No. 40. <https://doi.org/10.3390/geosciences14020040>
- [38] Helsel, D.R., Hirsch, R.M., Ryberg, K.R., Archfield, S.A. and Gilroy, E.J. (2020) Sta-

- tistical Methods in Water Resources, Techniques and Methods 4-A3. U.S. Geological Survey.
- [39] Chiang, F., Mazdiyasni, O. and AghaKouchak, A. (2021) Evidence of Anthropogenic Impacts on Global Drought Frequency, Duration, and Intensity. *Nature Communications*, **12**, Article No. 2754. <https://doi.org/10.1038/s41467-021-22314-w>
 - [40] Pyper, B.J. and Peterman, R.M. (1998) Comparison of Methods to Account for Autocorrelation in Correlation Analyses of Fish Data. *Canadian Journal of Fisheries and Aquatic Sciences*, **55**, 2127-2140. <https://doi.org/10.1139/f98-104>
 - [41] Blann, K.L., Anderson, J.L., Sands, G.R. and Vondracek, B. (2009) Effects of Agricultural Drainage on Aquatic Ecosystems: A Review. *Critical Reviews in Environmental Science and Technology*, **39**, 909-1001. <https://doi.org/10.1080/10643380801977966>